2. REQUIREMENTS FOR PHYSICS

2.1 INTRODUCTION

The primary aim of the Compact Muon Solenoid Collaboration is to discover new physics underlying the breakdown of electroweak symmetry. Several theoretical possibilities exist though the Higgs mechanism in the context of Supersymmetry is the favoured one. Many diverse experimental signatures from the new physics are possible involving high transverse energy muons, electrons, photons and jets. In order to cleanly detect these signatures the identification and precise energy measurement of muons, electrons, photons and jets over a large energy range and at high luminosities is essential.

CMS is a general purpose proton-proton detector designed to run at the highest luminosity ($L > 10^{34}$ cm^{-2} s^{-1}) at the LHC. The design has been optimised for the search of the Standard Model Higgs boson over a mass range 80 GeV - 1 TeV but it will also allow the detection of a wide range of possible signatures from alternative electro-weak symmetry breaking mechanisms. Although high luminosity is essential to cover the entire range of mechanisms of electro-weak symmetry breaking the LHC machine will start at significantly lower luminosities ($L \leq 10^{33}$ cm^{-2} s^{-1}) for which the CMS detector is also well adapted. Such studies of importance are CP violation in the B system and top quark studies. Another goal of CMS is to carry out specific studies of quark-gluon plasma (QGP) formation. One of the cleanest signatures of QGP formation will be the observation of anomalies in the production rates of heavy quark bound states J/y, y', and within the Y family.

The main design goals of CMS are:

i) a highly performant muon system,
ii) the best possible electromagnetic calorimeter consistent with (i),
iii) a high quality central tracking to achieve (i) and (ii),
iv) a hadron calorimetry with sufficient energy resolution and good hermiticity,
v) a detector costing less than 475 MCHF.

These goals are fulfilled by the CMS detector (see Fig. 1.1, p. C-1) whose distinctive features include a high solenoidal magnetic field (4 T) coupled with a multilayer muon system, a fully active scintillating crystal electromagnetic calorimeter and a powerful inner tracking system based on fine-grained microstrip and pixel detectors. These features allow a very good measurement of the energies of muons, electrons, other charged particles and photons, typically with a precision of about 1% at 100 GeV. Such a high precision leads to excellent mass resolution for states such as intermediate mass Higgs bosons, Z', B mesons in proton-proton collisions or Y states in heavy ion collisions. CMS is a compact and powerful spectrometer that is well matched to the physics potential of the LHC ranging from the elucidation of the electroweak symmetry breaking (search for the Higgs boson and supersymmetry), the study of CP violation, search for the signatures of the onset of quark-gluon plasma etc. Furthermore the use of a crystal calorimeter and pixel detectors considerably enhances the potential for discovery in CMS at the initially lower luminosities.

2.2 THE CHOICE OF THE FIELD CONFIGURATION AND PARAMETERS

The single most important aspect of the overall detector design is the configuration and parameters of the magnetic field for the measurement of muon momenta. The requirement for a good momentum resolution, without making stringent demands on the spatial resolution and the alignment of muon chambers, and keeping a compact spectrometer, leads naturally to the choice of a high magnetic field.

We have considered both toroidal and solenoidal fields. A solenoid is preferred for the following reasons:

a) with the field parallel to the beams, the bending of the muon track is in the transverse plane (see Fig. 2.2, p. C-2). In this plane the small transverse dimensions of the beams determines the transverse position of the vertex to an accuracy of better than 20 μm. The strong bending in the transverse plane facilitates the task of triggers based on tracks pointing back to the vertex.
b) momentum measurement in a solenoid starts at r = 0, while for a toroid it starts after the absorber, typically at r > 4 m. For a similar bending power the overall size of a solenoidal system is smaller than that for a toroid.

A long superconducting solenoid (L = 13 m) has been chosen with a free inner diameter of 5.9 m and a uniform magnetic field of 4 T. The favourable dimensional ratio (length/radius) of the solenoid and the high field allow efficient muon detection and measurement up to a pseudorapidity (η) of 2.4 (see Fig. 2.3, p. C-3). The muon spectrometer then consists of a single magnet allowing for a simpler architecture for the detector. The inner coil radius is large enough to accommodate the inner tracker and the calorimeters. The magnetic flux is returned via a 1.5 m thick saturated iron yoke instrumented with four stations of muon chambers. The yoke is thick enough to allow safe identification and powerful trigger on muons.

2.3 THE BENEFITS OF A MAGNETIC FIELD OF 4T

A high magnetic field is mandatory for a compact detector based on a single and long solenoid detector. A field of 4 T brings substantial benefits not only for the muon tracking and inner tracking but also for electromagnetic calorimetry. To illustrate this we shall compare the performances between two field choices, 4 T and 3 T.

2.3.1 Muon momentum resolution and trigger

One of the main arguments in favour of a strong magnetic field is to enable an efficient first level trigger.

Efficient triggering on muons is a difficult task in hadron colliders. So far all hadron collider experiments triggering on muons have had to make substantial improvements after initial data taking. From the outset the CMS philosophy has been to optimise a design which assures a powerful trigger without compromising the performance of other parts of the detector. The goal is to achieve sharp trigger thresholds in order to keep first level trigger rate low and hence avoid a hardwired 2nd level trigger. At a muon p_t threshold of 20 GeV the muon trigger rate almost doubles going up from 6 kHz to about 10 kHz when the magnetic field goes down from 4 T to 3 T (see Fig. 2.1).

The robustness of the CMS muon trigger relies on two independent measurements. The first and the more precise one relies on the measurement of the direction of the muon in the first muon station in the transverse plane. Lowering the field would require a corresponding improvement in the spatial accuracy in the muon chambers. The second one uses the measurements in all four muon stations. This takes on great significance when the first muon station is spoiled which happens for about a quarter of the muons. The magnetic flux generated by a 4 T central field is sufficient to saturate 1.50 m of iron in the return yoke. For a 3 T field, the bending power is reduced by 25% and only around 1.1 m of iron can be saturated. Four muon stations are required for a muon system that is robust, redundant and provides full geometric acceptance. Installation of four muon stations in a reduced thickness of 1.1 m is not optimal. At 3 T these factors lead to a system that is too marginal to be acceptable in light of the difficulties encountered by all the hadron collider experiments so far.

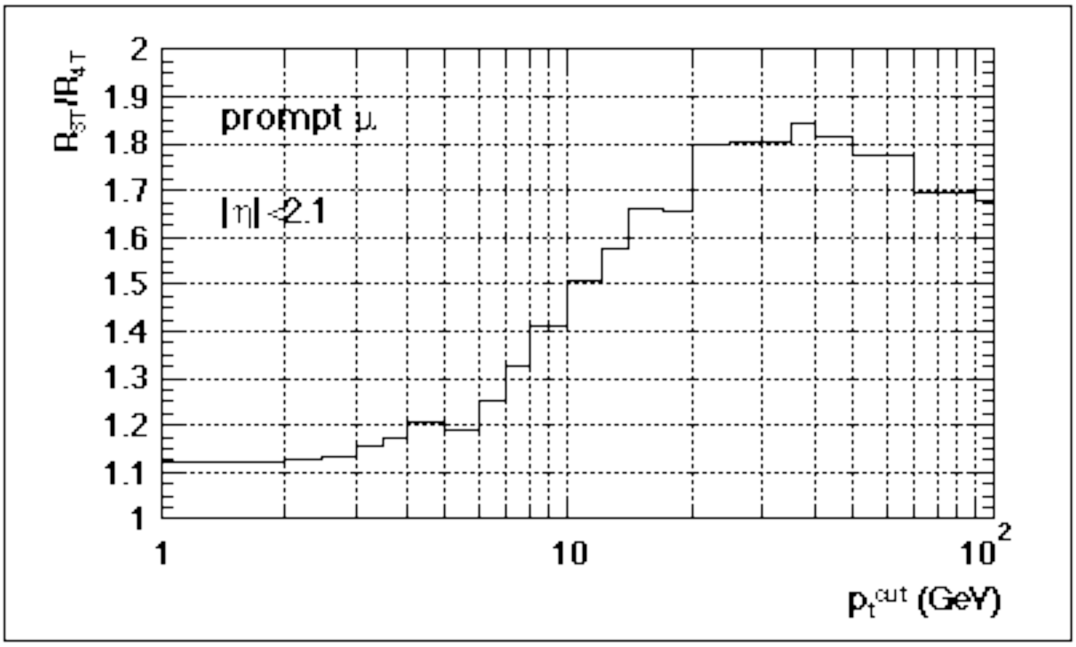

Fig. 2.1: The ratio of trigger rates for single muons for fields of 3T and 4T.

2.3.2 Inner tracking and momentum resolution

Reducing the field from 4 to 3 T will lead to a corresponding deterioration of the momentum resolution. The mass resolutions for multi charged particle states are given in Table 2.1. For a signal of a given significance, involving such states, the percentage additional running time required increase by one third when the field is lowered to 3 T from 4 T.

Table 2.1
Mass Resolution for various states at 4 and 3 T.

State	Mass Resolution at 4 T	Mass Resolution at 3 T
H_{SUSY}(300 GeV) ® ZZ ® 4m	2.1 GeV	2.8 GeV
H_{SM}(150 GeV) ® ZZ* ® 4m	0.8 GeV	1.1 GeV
B^0_d ® p p	27 MeV	36 MeV
Y ® mm	36 MeV	48 MeV

When changing from 4 T to 3 T the occupancy increases in the inner tracker by about 40% in the outermost regions of the barrel region and by about 25% in the outer parts of the forward disks. In contrast, it decreases by about 20% in the innermost areas like the Si barrel.

The outer regions play an essential role for muon track reconstruction in heavy ion running. The difference is expected to be even larger in heavy ion running as the mean p_t is expected to be smaller and hence more tracks are expected not to reach the outer regions for a field of 4 T. This considerably improves the pattern recognition capability and the muon track reconstruction efficiency. In fact the strip length of the MSGCs has recently been reduced from 25 cm to 12.5 cm precisely to halve the occupancy to enable good muon track reconstruction efficiency for heavy ion running.

2.3.3 Electromagnetic calorimetry

Maximum benefit from a crystal electromagnetic calorimeter can only be derived if it can be calibrated to an accuracy of a fraction of a percent. This is possible by using copiously produced isolated electrons from the production of Ws, Zs and b-quarks. The energy of electrons measured in the calorimeter can be compared with their momenta measured in the tracker. The number of electrons required is proportional to the square of the standard deviation of the quantity energy/momentum. Optimally both the inner tracking momentum and the electromagnetic calorimeter energy resolutions should be comparable in the relevant range of the energy of electrons. At present this indeed is the case and the two resolutions are evenly matched. Lowering the field to 3 T will make the inner tracking resolution the limiting one and the number of electrons required for a given accuracy of calibration will increase by up to 50%. The period for a calibration with sufficient precision will typically be of the order of a month at the lower luminosity of L ~10^{33} cm^{-2} s^{-1}.

One of the features of the large magnetic field is the trapping of charged particles inside the tracking cavity. The flux of charged particles reaching the ECAL is therefore reduced. The charged particle transverse energy density for different values of field and pseudorapidity are given in Table 2.2. The reduction with increasing field is significant.

Table 2.2
Charged particle energy density/minimum bias event/m^2 in the electromagnetic calorimeter.

Magnetic Field	Mean Transverse Energy Density (GeV/m^2)		
	Barrel		Endcap
	|h| = 0	|h| = 1.5	|h| = 2.4
0 T	0.5	0.55	1.3
2 T	0.3	0.25	0.7
4 T	0.15	0.1	0.4

2.4 CONCLUSIONS

Lowering the magnetic field in CMS to 3 T or below would result in a permanent reduction of the physics performance. Safety margins in the inner tracking, for the overall momentum resolution, effective mass resolution, calorimeter energy pileup and especially for the muon trigger are eroded. There is an overwhelming consensus in the Collaboration that a field substantially higher than 3 T is central to the concept of CMS. In designing a coil of 4 T it is understood that a field of at least 3.5 T will be guaranteed.